Efficient absolute aspect determination of a balloon borne far infrared telescope using a solid state optical photometer

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ABSTRACT

The observational and operational efficiency of the TIFR 1 meter balloon borne far infrared telescope has been improved by incorporating a multielement solid state optical photometer (SSOP) at the Cassegrain focus of the telescope. The SSOP is based on a 1-D linear photo diode array (PDA). The online and offline processing schemes of the PDA signals which have been developed, lead to improvement in the determination of absolute telescope aspect ($\sim 0\overset{\prime}{.}8$), which is very crucial for carrying out the observations as well as offline analysis. The SSOP and its performance during a recent balloon flight are presented here.

Subject headings: instrumentation : photometers — space vehicles : instrumentation

1. Introduction

The Tata Institute of Fundamental Research (TIFR) 1 meter balloon-borne far infrared (FIR) telescope is flown regularly to carry out observations of Galactic star forming regions, external spiral galaxies etc (Daniel et al 1984; Bisht et al 1989). The orientation and pointing system of this telescope uses a star tracker (ST) as a two axis angular position sensor (Almeida et al 1983; Ghosh & Tandon 1982). A bright optical guide star, $m_B < 5$, within the field of view (2°) of this ST, provides the positional reference. Since the space angle between the nearest usable guide star and the FIR target (η), is typically $> 3°$ the star tracker is mechanically offset with respect to the main telescope about the two main control axes (viz., elevation & cross-elevation). The mechanical offset system allows for $\pm$ 4$^{\circ}\!\!.$5 motion about each axis (in steps of $\approx 20''$). The mechanical offsetting of the ST is effected by a pair of stepper motor driven screws through trains of gears, whose positions are measured by shaft encoders. Although the pointing jitter of the telescope orientation system is $\approx 20''$rms (adequate for observations at 200 μm, where the diffraction limit is $50''$), the achieved absolute positional accuracy is only $\approx 2 - 4'$ (for $\eta > 3°$) due to fabrication defects of mechanical components. The above implies the necessity of in-situ absolute position calibration of the Cassegrain focal plane of the telescope. In the past, a focal plane photomultiplier tube (FPPM) based optical photometer (sensitive upto $m_B = 9.0$, for 3 sec integration, typical of observational rasters) has been used successfully to improve the absolute aspect accuracy to $\sim 1'$ for η as large as 5° (Ghosh et al 1988, Das & Ghosh 1991). With the introduction of bolometer arrays in our two band (12 channel system; Verma, Rengarajan & Ghosh 1993) FIR photometer, the use of the FPPM (which is effectively a single pixel device) for achieving absolute aspect, leads to very poor observational efficiency. The multi element solid state optical photometer (SSOP), is a solution which is briefly described in this paper. Sections 2 and 3 describe the SSOP and the relevant software processing schemes. The results from a recent balloon flight, which quantify its performance, are presented in Section 4.

2. Solid State Optical Photometer

In order to achieve a good observational efficiency, the FOV subtended by the entire detector-array of the FIR instrument must at least be covered by the SSOP. The SSOP has to detect stars while FIR observations are in progress (e.g. the sky is chopped by wobbling the secondary mirror at 10 Hz; and scanned at 0.5–1.0 arc min/sec). These requirements translate to : resolution element $< 1'$; sensitivity of $m_R \sim 10$ (for integration time corresponding to the typical raster scan); and a dynamic range of $\sim 10^4$.

The detector selected is an EG&G Silicon Photodiode array, PDA-20-2, with 20 elements. Each element is 0.94 mm x 4.0 mm in size and the pitch is 1.0 mm resulting in a very small dead zone. It has a NEP of 7×10^{-15} W Hz$^{-1/2}$ (at +23° C) and an operating temperature range of +70° C to -55° C (ambient temperature at balloon float altitude is ≈ -50° C). Two consecutive elements are hardware "binned" (by connecting them in parallel) to implement an effective "pixel" of $0\overset{\prime}{.}87$ (El) x $1\overset{\prime}{.}7$ (XEl) size, at the Cassegrain focal plane of the 1-meter (f/8) telescope. Only 16 of the 20 elements of the PDA have been used (i.e. 8 pixels). Hence, the used part of the PDA (1 pixel × 8 pixel array) subtends an angle of $1\overset{\prime}{.}7 \times 6\overset{\prime}{.}9$ on the sky. A two stage baffle with opening corresponding to ≈ f/7 precede the PDA. The PDA has reasonable spectral response from 5000 Å to 10500 Å with a peak responsivity of 0.6 A/W at 9000 Å.

The PDA is used in the photovoltaic mode. A bank of trans-impedance amplifiers, TIAs, pre-amplify signals from each pixel (see Fig. 1), which are placed physically close to the PDA inside a EMI insulated chamber. The preamplified signals are buffered and fed to the 8 channel detector signal processing unit (DSPU). Each DSPU channel consists of : attenuator, buffer, composite band pass filters, phase sensitive detector (PSD), low pass filter and interface to the telemetry system (see the DSPU block diagram in Fig. 2). The final DSPU outputs from all 8 pixels are sampled at 10 Hz and digitized (12 bit ADC) by the telemetry down-link.

Since low frequency / DC drifts of the PDA signals are lost in PSD processing, two selected pixels of the PDA are additionally processed through DC-coupled stages (with much lower gain to avoid electronic saturation) and sampled at about 0.3 Hz. This is useful to monitor the background light level and the dark current.

3. Software for SSOP

3.1. Online processing

The PDA signals are processed online at the ground station, while the telescope scans a pre-selected optical star in a clean field near the far infrared target (within 20–30′). The results from this processing are used to update the telescope model for absolute aspect.

The signals from all the PDA pixels and the data from the sensors relevant for the telescope aspect (all sampled at 10 Hz) are stored in a time sequence for each scan line. The time sequence of the PDA signals for each scan line are convolved with a function which represents the PDA response for scan across a star

(including the effect of sky chopping). The time corresponding to the grand maximum of the convolved signal sequence provides the telescope aspect corresponding to the target star. The resulting aspects from several relevant scan lines are combined to update / refine the existing model for the telescope aspect.

3.2. Off-line processing

The off line data processing involves determination of the instantaneous telescope boresight using the data from the two axis angular position (Star Tracker) and rate (Gyroscopes) sensors used in the telescope orientation and stabilization system (Ghosh et al 1988). The chopped SSOP signals (all 8 pixels) are gridded in a two dimensional sky matrix (the two axes representing the telescope coordinate system, viz., elevation & cross elevation). Signals from all 8 pixels of SSOP are mixed using a focal plane model of their relative location, which is determined during laboratory testings prior to the launch. The telescope raster scans are parallel to the cross elevation axis. The cell size used in this observed (chopped) signal matrix is $0'.3 \times 0'.3$. This observed signal matrix is deconvolved using an indigeneously developed scheme using the Maximum Entropy Method (MEM) similar to Gull and Daniell, 1978 (see Ghosh et al., 1988, for details). The 2-D point spread function (PSF) used in the MEM scheme is determined from the scans across a bright star during the balloon flight. The positions of the peaks in the deconvolved optical map represent detected stars which are compared with various catalogues (SAO, HST Guide Star Catalogue etc) to quantify any systematic shifts / effects.

4. Performance of the SSOP

The SSOP system was flown during the balloon flight of the 1-meter far infrared telescope payload on March 8, 1998, from Hyderabad, in central India. The payload was at the float altitude of 31 km for 5.5 hours. During this flight, several bright stars were scanned using SSOP (and sometimes using the FPPM) to confirm the focal plane model and establish the absolute aspect of the telescope. In addition, during the scans across the FIR programme targets, the SSOP has covered typically 600 square arc min of the sky (Ghosh 1998).

The 2-D Point Spread Function (PSF) of the SSOP (corresponding to one pixel) has been generated from the observations of the star ρ Pup. The FWHM for a point source (BS 6546) after MEM deconvolution is found to be $0'.85 \times 1'.62$ (Elev $\times$ Cross-elev), which is very close to the expected value.

The off-line processing has been carried out for 9 mapped regions, each covering about $30' \times 25'$ area. Figure 3 shows the resulting optical isophot contour map from a typical observation. The brightest and the faintest star in this map correspond to m_R of 7.06 and 9.76 respectively. Clear detections of well identified stars are marked on this map. A total of 40 stars have been detected and identified in these 9 fields. The final absolute map coordinates are determined from the shift parameters (ΔRA, ΔDec) which best align the peaks of the map with the coordinates of identified stars. For the present sample of 9 regions mapped, the shift angle ($\theta_{corr} = \sqrt{\Delta RA^2 + \Delta Dec^2}$) is found to be increasing with, η, the offset angle between the telescope axis and the Star Tracker axis. The RA and Dec components of the residual angles (res_α, res_δ) show a gaussian distribution (see Fig. 4). The standard deviations ($\sigma(res_\alpha) = 44''$; $\sigma(res_\delta) = 29''$) reflect the ultimate absolute aspect errors in the final maps and quantify the cumulative effects of pointing jitter; electronic and data processing noise; and the quality of telescope optics (the primary & secondary mirrors are designed for FIR wavelengths and hence are very poor for optical wavelengths). By dividing the entire sample into two categories on the basis of the offset angle η ($\eta > 2^0$; & the rest), it has been found that $\sigma(res_\alpha)$ & $\sigma(res_\delta)$ are not sensitive to η. Hence, using the SSOP, it has been possible to achieve an absolute aspect accuracy of $\approx 0\farcm8$, in the presence of mechanical imperfections leading to 1.5–4$'$ errors.

The spectral response of the PDA elements is such that the m_R magnitude of stars represents the signal expected from the SSOP. A total of 22 stars, for which m_R could be found / estimated from the literature, have been used to calibrate the SSOP and quantify the system linearity and sensitivity. The SSOP is found to be linear within the testable range of $2 < m_R < 9.7$. The faintest star detected corresponds to $m_R = 10.9$ in our sample. The expected sensitivity for the SSOP (for identical observational conditions) is $m_R = 10.0$. Hence, the achieved sensitivity is quite close to its design goal.

The analysis of the DC coupled channels (2 of the 8 pixels) implies a large increase in the scattered light background near the telescope focal plane during the time when moon (illuminated fraction = 0.82) was above horizon. The maximum observed background corresponds to $\approx$ 14.9 mag (m_R) arcsec^{-2}.

5. Conclusions

A multielement solid state optical photometer (SSOP) has been developed and successfully used at the Cassegrain focal plane of the TIFR 1-meter balloon borne far infrared telescope. This SSOP has been used on-line as well as off-line to achieve higher absolute positional accuracy ($0\farcm8$) of the telescope during a balloon flight. The achieved sensitivity of the SSOP corresponds to the stellar magnitude of $m_R \sim 10.0$ (for typical

raster scans used for FIR targets) which is consistent with the expectations. The SSOP has also improved the observational and operational efficiency of the telescope.

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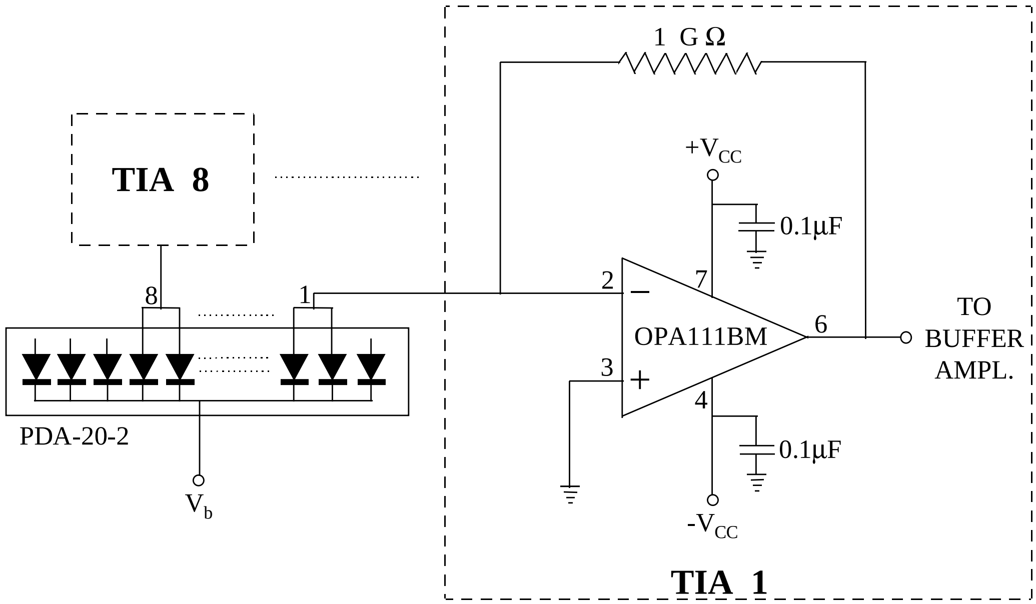
Fig. 1.— The Trans-Impedance Amplifier (TIA) used to preamplify the signals of the Photo Diode Array (PDA) elements. Each pixel comprises of two PDA elements, and 8 pixels have been used for the Solid State Optical Photometer (SSOP).

Fig. 2.— Block diagram of the on-board Detector Signal Processing Unit (DSPU) of the SSOP.

Fig. 3.— In-flight SSOP optical map of the region near IRAS 17160-3707. The contour levels are 95%, 90%, 80%, 70%, 60%, 50%, 40%, 30%, 20%, 10%, 5%, 2.5% and 1% of the peak intensity, which is = 7.67 mag (m_R) arcmin^{-2}. The symbol + represents detected and identified stars; and the dots mark the boundary of the region mapped.

Fig. 4.— The distributions of the (a) RA and (b) Dec components of the residuals (res_α & res_δ), after applying the correction (see text). The smooth curves denote the best fit gaussians. The means (μ) are approximately zero as expected and the standard deviations (σ) quantify the achieved absolute aspect accuracy.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+V$_{CC}$
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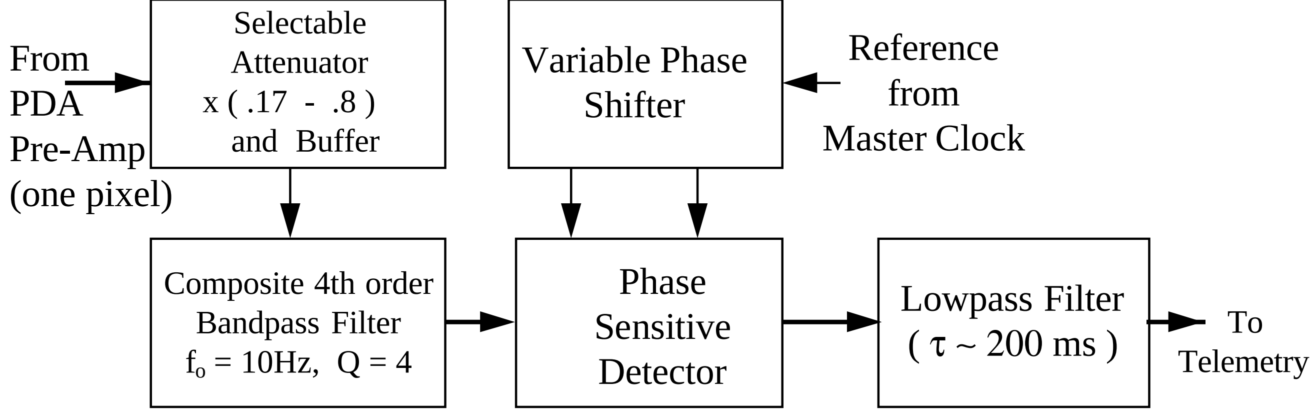
TIA 1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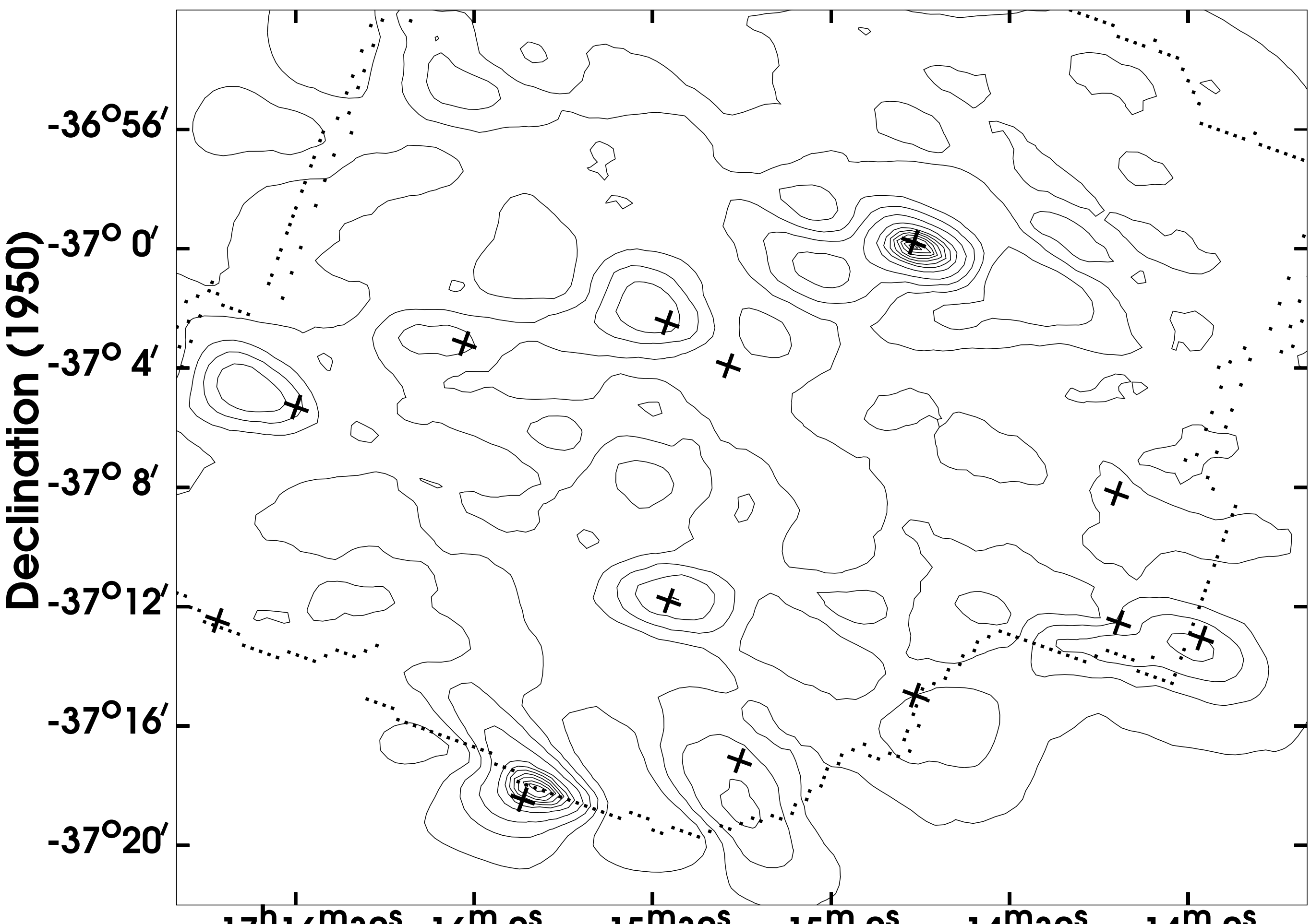
Phase Sensitive Detector
Lowpass Filter ($\tau \sim 200$ ms)
To Telemetry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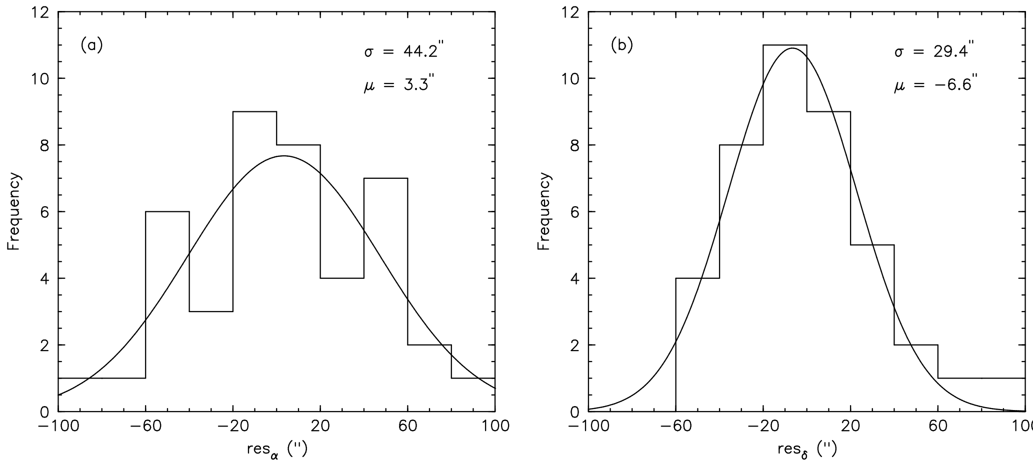
Right Ascension (1950)



(a)
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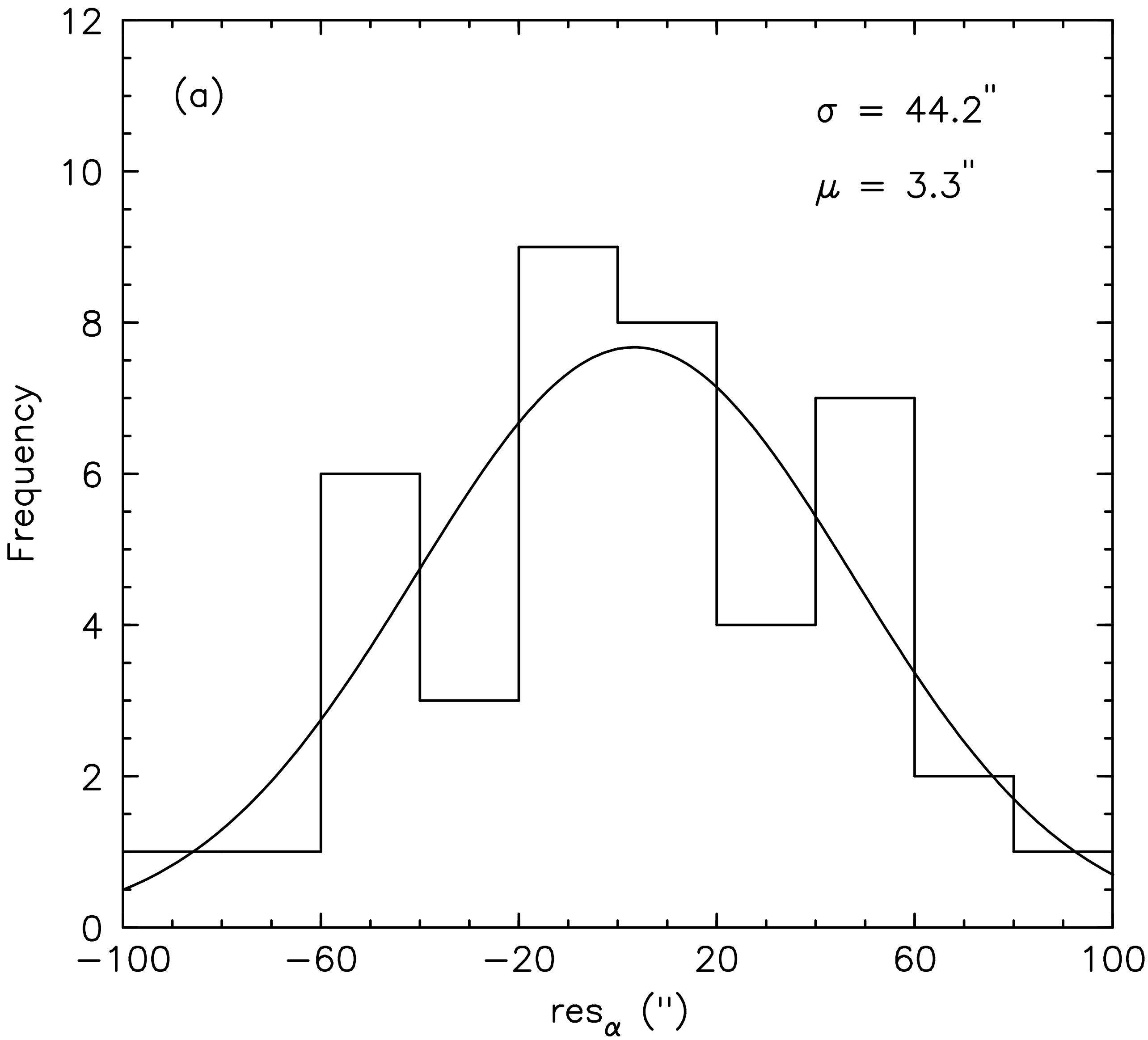
μ = 3.3"
Frequency
res_α (")
(b)
σ = 29.4"
μ = −6.6"
Frequency
res_δ (")


(a)
σ = 44.2''
μ = 3.3''
Frequency
res$_\alpha$ ('')
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6
8
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12
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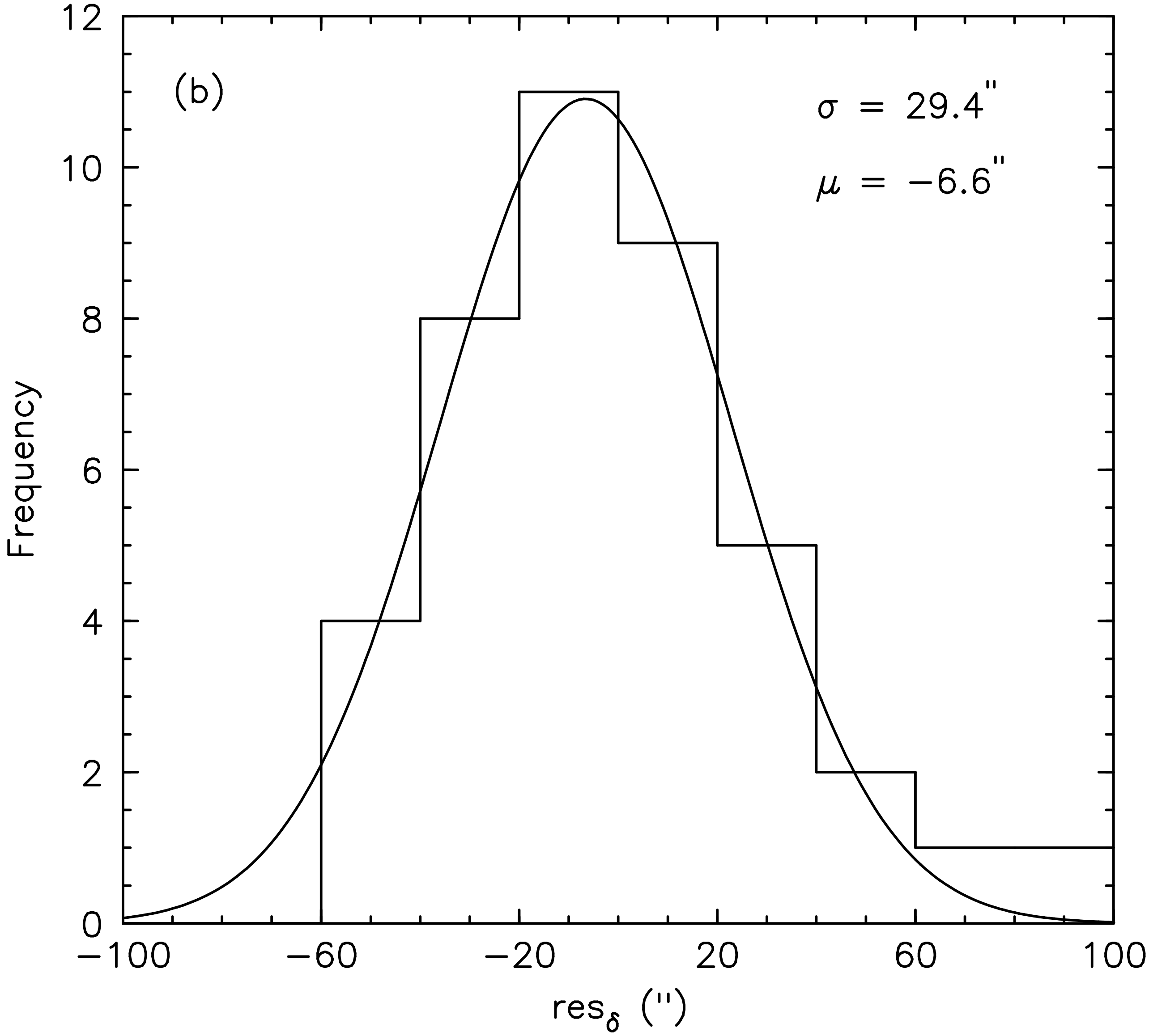
−60
−20
20
60
100


(b)
σ = 29.4''
μ = −6.6''
Frequency
res_δ ('')
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2
4
6
8
10
12
−100
−60
−20
20
60
100